Challenges for Planetary Rover Navigation

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Overview

- **Planetary rover design has unique requirements**
  - Environmental
  - CPU and sensor limitations on control algorithms
  - Style of commanding
  - Fault Responses
- **Case study: MER solution**
  - Mars Equatorial solar-powered environment
  - Single CPU impact on surface autonomy
  - Once-per-day commanding
  - Stop and wait vs autonomous responses
- **Challenges for future missions**

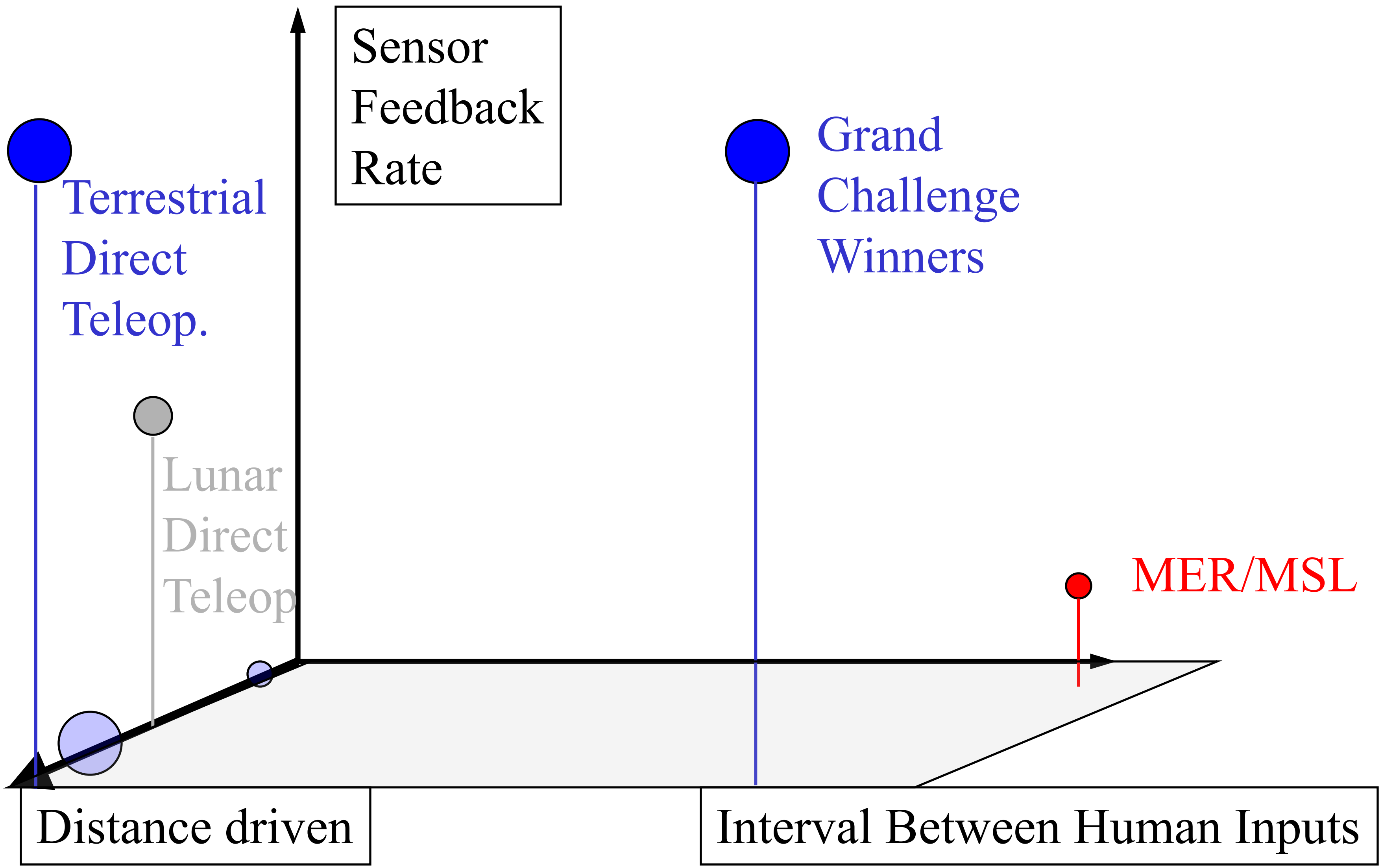
Environmental Constraints

- **Terrestrial rover design has tremendous flexibility**
  - Wheels, legs, treads
  - High power available via human-provided refueling sources
- **Planetary rovers have to rely on low power and KISS (Keep It Simple, Somebody) design**
  - More motors or more actuators are more things that can go wrong
  - You get what you get: mission survivability trumps robotic capability
- **Low power means slow driving and slow processing**

CPU and Sensor Limitations

- **Terrestrial vehicles use state of the art CPUs and sensors**
- **Rover equipment must survive the cruise and surface environments**
  - Proven, space-qualified devices are typically a decade or more out of date
  - CPUs are much slower: Sojourner 0.1 MHz, MER 20 MHz
  - Sensors can be much slower and are more limited in number
- **Algorithms must be tailored to the current system**
  - Visual Odometry example: slow image acquisition time dictates large distance between steps, necessitating more robust tracking software than needed for terrestrial operations
  - Hazard Detection example: plan to use the minimum number of images needed to ensure proper obstacle detection

Mobility Autonomy Design Space



Style of Commanding

- **Direct teleoperation does not work (except on the Moon)**
  - Typically only one chance to send commands each day
  - Send a series of conditional, event-driven commands
- **Goal designation is different:**
  - On Earth, a goal might be set using a live beacon, or GPS coordinates
- **Planetary rover Goal designation has multiple error sources:**
  - Target specification error: locating the rover with respect to the goal at its initial position
    - Stereo range resolution dominates in rover-taken images, initial rover localization and map projection resolution dominate in infrequently-taken orbital images
  - Ensuring the proper goal has been reached at the end
    - Must either track the goal or carefully update rover position estimates along the way

Fault Responses

- **There is no kill switch**
  - The rover has to be programmed to be more conservative
- **Some faults are worse than others**
  - Surface operations are different than cruise operations
  - Fault behavior can be tailored to the current terrain
- **The command language needs to be designed to allow autonomous fault detection and recovery**
  - Must allow the system to be retuned for different types of terrain; we don't have smart enough sensing to autonomously switch behaviours based on terrain yet
  - Adding contingencies into the plan for benign or expected faults will improve overall mission return
- **Plan for degraded operations when components fail**

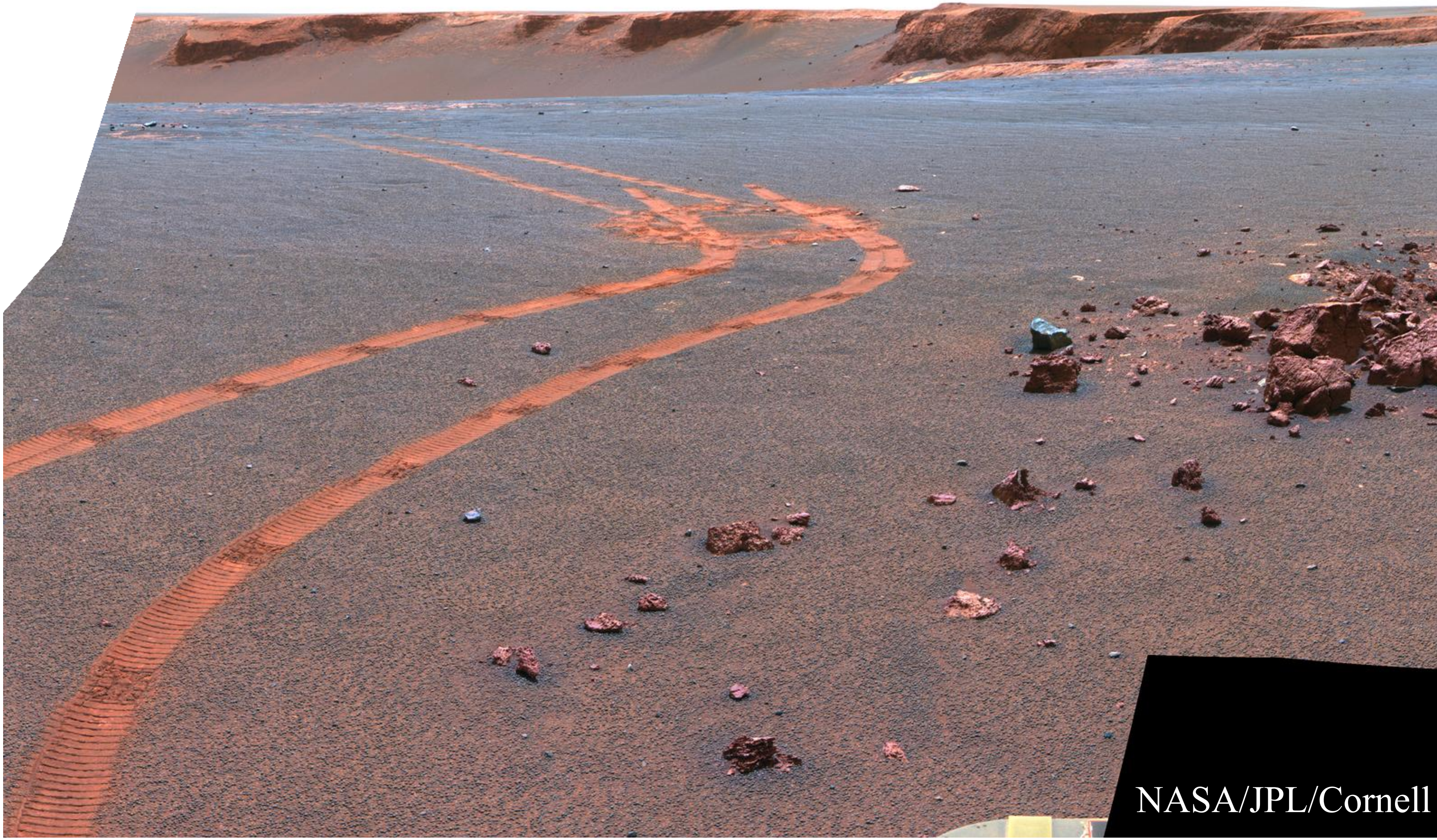
MER Design due to Environment and KISS

- **Low power: Nominal mission planned to succeed even with limited power**
- **Slow driving: Wheel motor gear ratios were determined by the needs of worst-case climbing**
  - So it can climb over obstacles, but its top speed is limited even in benign terrains
- **Limited sensing**
  - No camera can see the middle wheels or under the rover
  - A small number of cameras was chosen to minimize the power required and system integration complexity

MER CPU and Sensor Limitations

- **Slow processing: we use the same CPU for Launch, Cruise, Entry/Descent/Landing, and Surface operations**
  - Even though surface operations do not require the same robustness as the other phases
  - CPU speed also limited by available power
- **Slow sensing: Cameras, motors, CPU must survive extreme temperatures and use minimal power**
  - Cameras take excellent images, but 10 seconds are needed just to transfer a stereo pair of 1 Megapixel images into RAM
- **This impacts the design of autonomy algorithms and puts constraints on their use during operations**

Most MER Autonomy



MER Style of Commanding

- **A series of event-driven conditional commands is updated each drive day**
- **Drive goals are normally specified using X,Y,Z**
  - Short range drive goals (< 20 m) from onboard Navcam range data
  - Long range drive goals from Pancam range data or orbital images
- **Only goals that allow for accumulated position estimation error are selected**
  - Position error can be minimized by enabling Visual Odometry
- **Visual Target Tracking can eliminate target specification error**
  - Constantly re-estimating target location visually during a drive

MER Fault Responses

- **Two classes of driving faults: Goal and Motion Errors**
  - Goal Errors simply indicate the planned location wasn't achieved; the vehicle is still safe
  - Motion Errors indicate some system parameter is out of range, e.g., motor current, vehicle tilt
    - But ranges are selected to ensure overall vehicle safety; even if "out of range", you can still have sufficient power and communications
- **Command sequences can behave conditionally on fault type**
  - The more time you have, the more alternatives you can plan for
- **Unplanned faults leave the vehicle in a safe state**
- **Both MER vehicles are dealing with failed motors, yet continue to perform useful science**

Spirit Finds Salts by Home Plate A-721

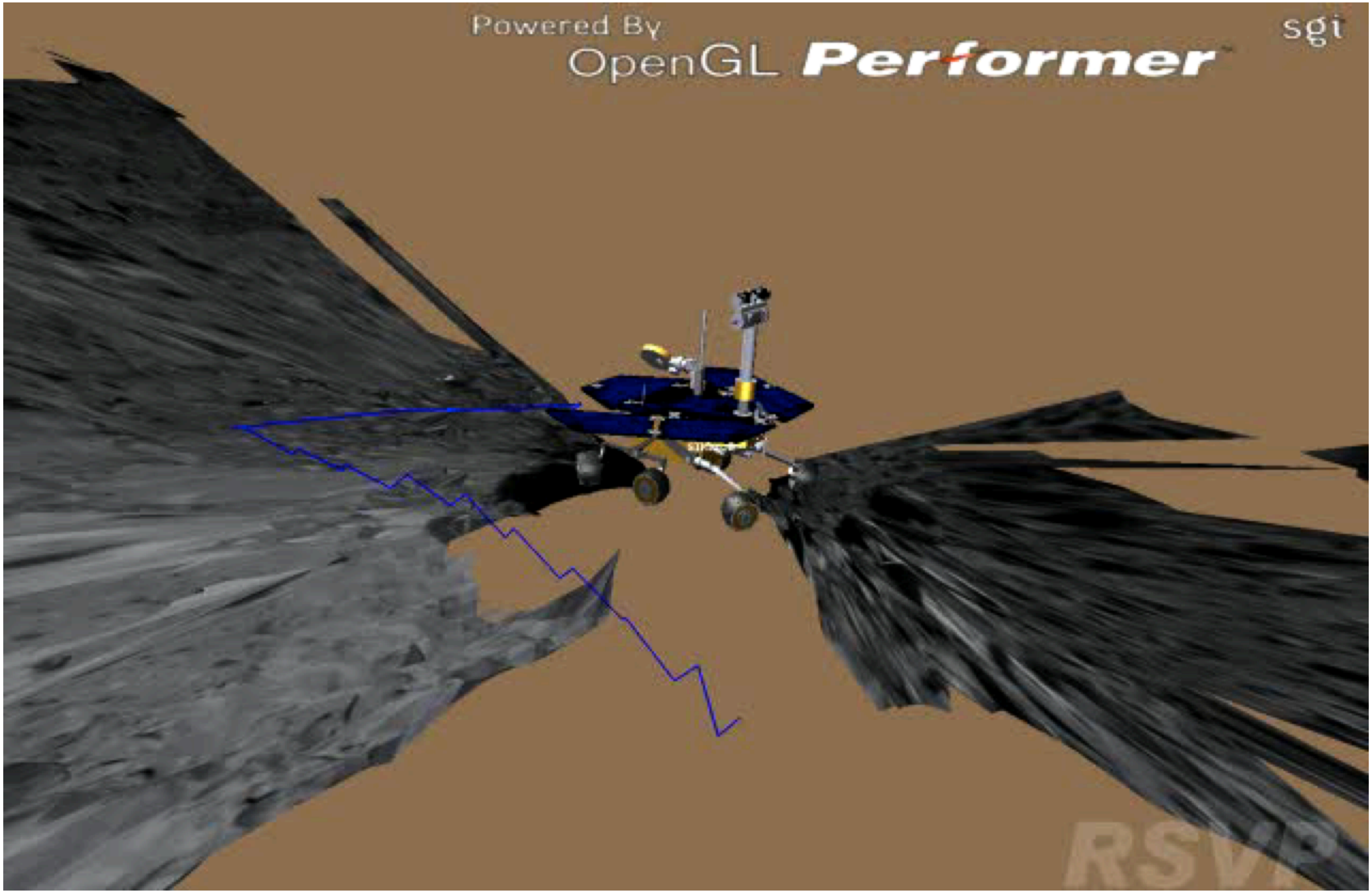
Future Missions: Focus on Telemetry

- **Rover telemetry requirements differ from terrestrial systems**
- **Make drive behavior reproducible**
  - Make sure you provide enough data to understand vehicle behaviour
  - Include occasional images of tracks
- **Priority matters**
  - Bandwidth may be limited, so high level summaries and error status are given the highest priority
- **Redundancy helps**
  - Telemetry transmission may be interrupted or lost at any point, so there may only be partial data

MER Partial Data

- **Each rover generates dozens or even hundreds of separate pieces of data each sol**
- **Not all generated data is received at Earth the same day**
  - There is limited bandwidth throughout the communication chain
    - (rover -> orbiter -> deep space network)
  - Bad weather at the Deep Space Network antenna could corrupt data
- **Certain information is replicated in many forms**
  - E.g., rover X,Y,Z position appears in EH&A, certain EVRs, and multiple data products
- **Over 600 distinct fields are automatically extracted from multiple sources and given a unique name**
  - Users generally do not care exactly how the information was collected (I.e., the source of the data), but they do want to see every value downlinked
    - Example: Course plot

Telemetry Needs



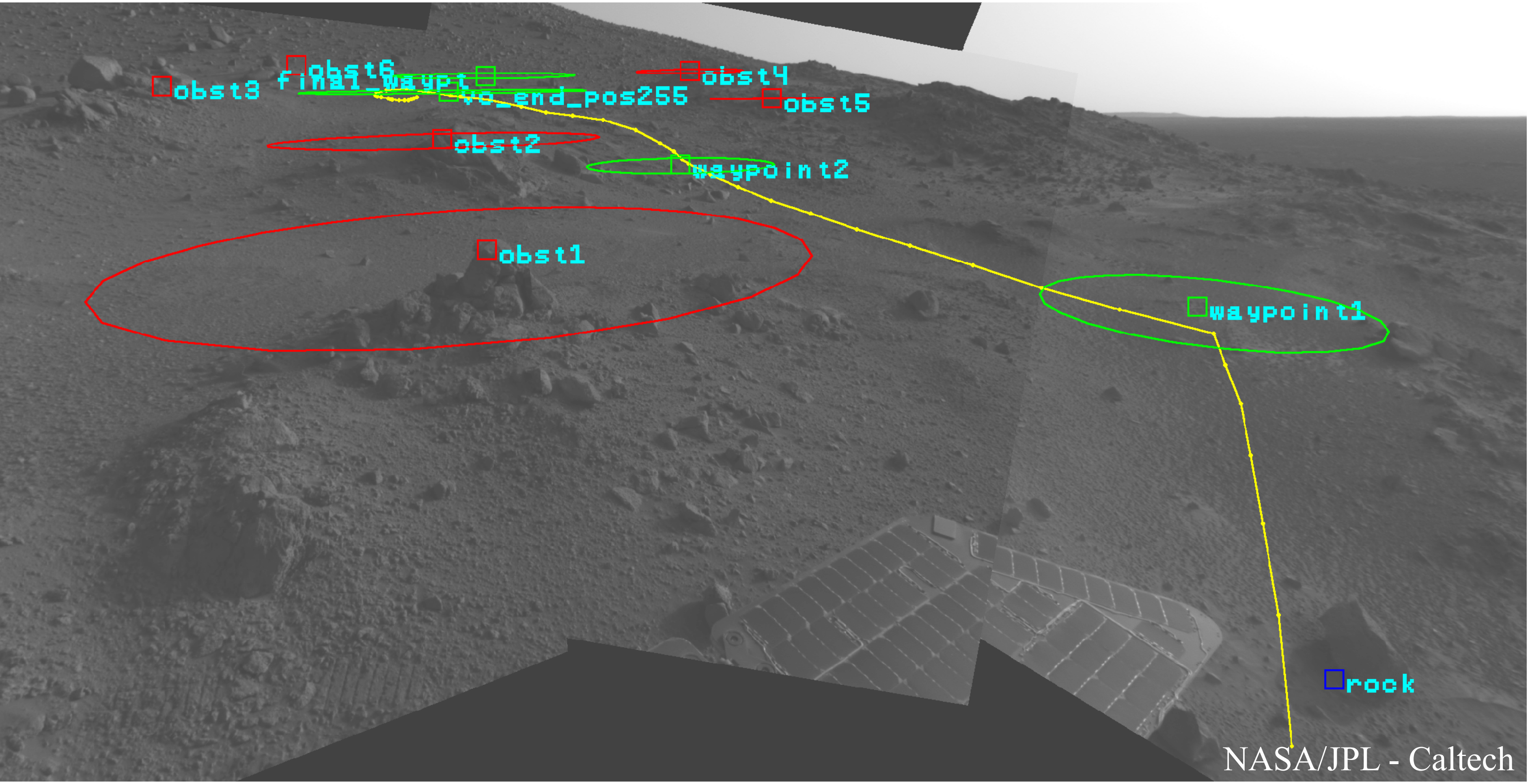
Future: Resource Modeling

- **Any autonomy technology transitioning to flight must include a prediction of its CPU resource use as a function of sensed data size (e.g., image resolution)**
  - RAM, CPU time
- **Rover operations team will need to model overall system resource use during each day:**
  - Power
  - Time required
  - Data Volume

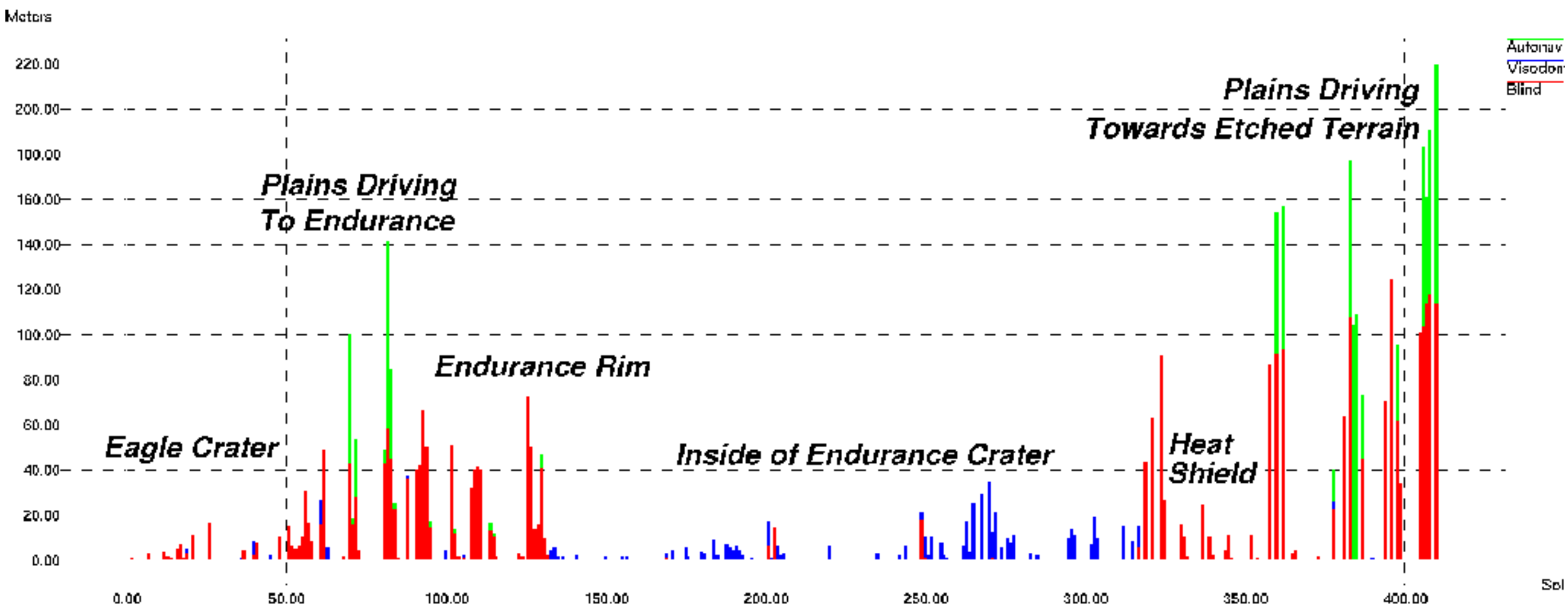
Future: Robust Terrain Adaptation

- **Geometric hazard avoidance and basic Visual Odometry have already been proven useful by MER**
- **Long distance autonomy will require better adaptation to novel terrain**
  - MER had to be manually configured for each terrain type, even within a single drive
  - Autonomous adaptation to local terrain would improve long-range performance
    - Based on actual slip measurements, terrain geometry, terrain texture, possibly onboard science analysis

Pre-drive Annotation: A-436

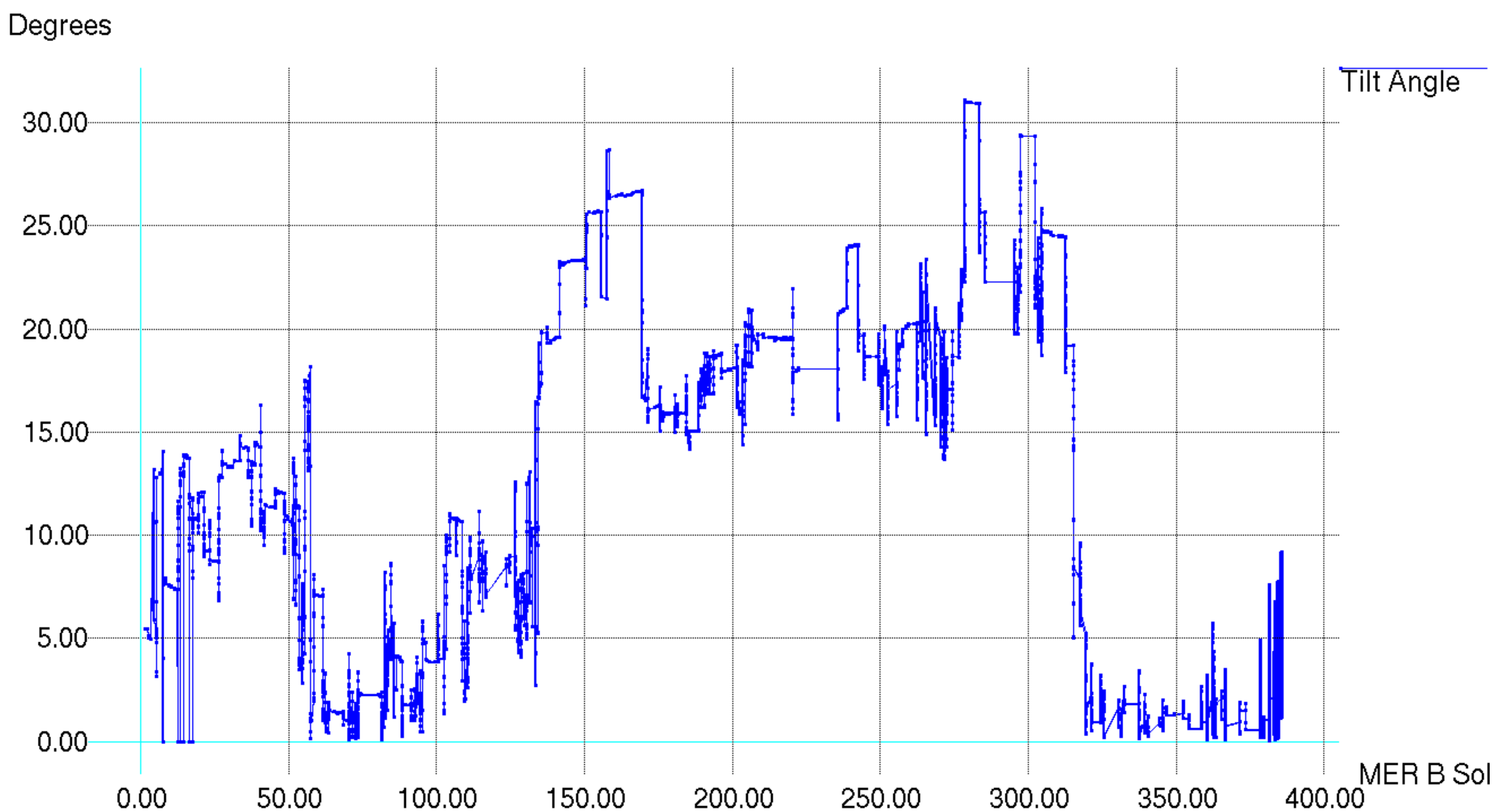


Opportunity Drive Modes in first 410 Sols



Data from rover's onboard position estimate

Opportunity Tilt History through Sol 380



Future: Focus on target approach

- **Some of the most interesting science results derive from in situ observations by instruments mounted on manipulator arms.**
- **MER demonstrated components of single sol instrument placement**
  - Visual Odometry, Visual Servoing, IDD (arm) Autoplacement
- **But future goal specifications should consider not only X,Y,Z position, but also kinematic constraints on how the target will be sampled or studied upon arrival.**

Conclusion

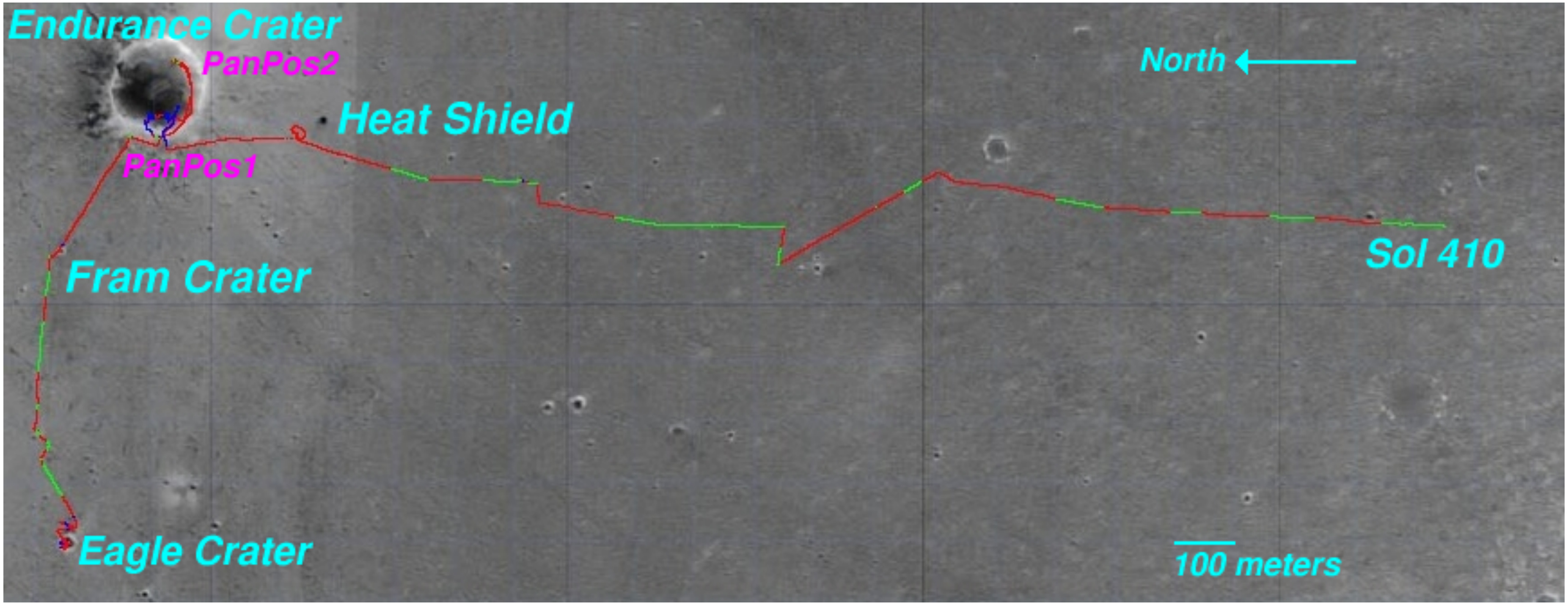
- **Planetary robots can take advantage of many new robotic technologies**
  - But only if they are tailored to the mission constraints
- **Faster processors would improve autonomy behavior, but not by orders of magnitude**
  - Mechanical and other sensor bottlenecks quickly come into play
- **More focus needed on reducing the number of days spent at a science feature**
  - Most time is spent performing in situ work at science targets, efficiency improvements there will have a large impact on overall mission science return

BACKUP SLIDES

MER Downlink Needs

- **Driving and operating the arm on the Mars Exploration Rovers daily requires a rapid understanding of what happened during the previous day.**
- **This immediate ("tactical") analysis must be performed:**
  - Even when only a *partial* view of what happened is available,
  - By people who may be working over a slow remote connection,
  - Quickly enough to be useful to the current day's planning activities.
- **Long term ("strategic") analyses are also needed:**
  - To understand the recent multi-day history of a stalled actuator
  - To monitor overall vehicle health during the entire mission

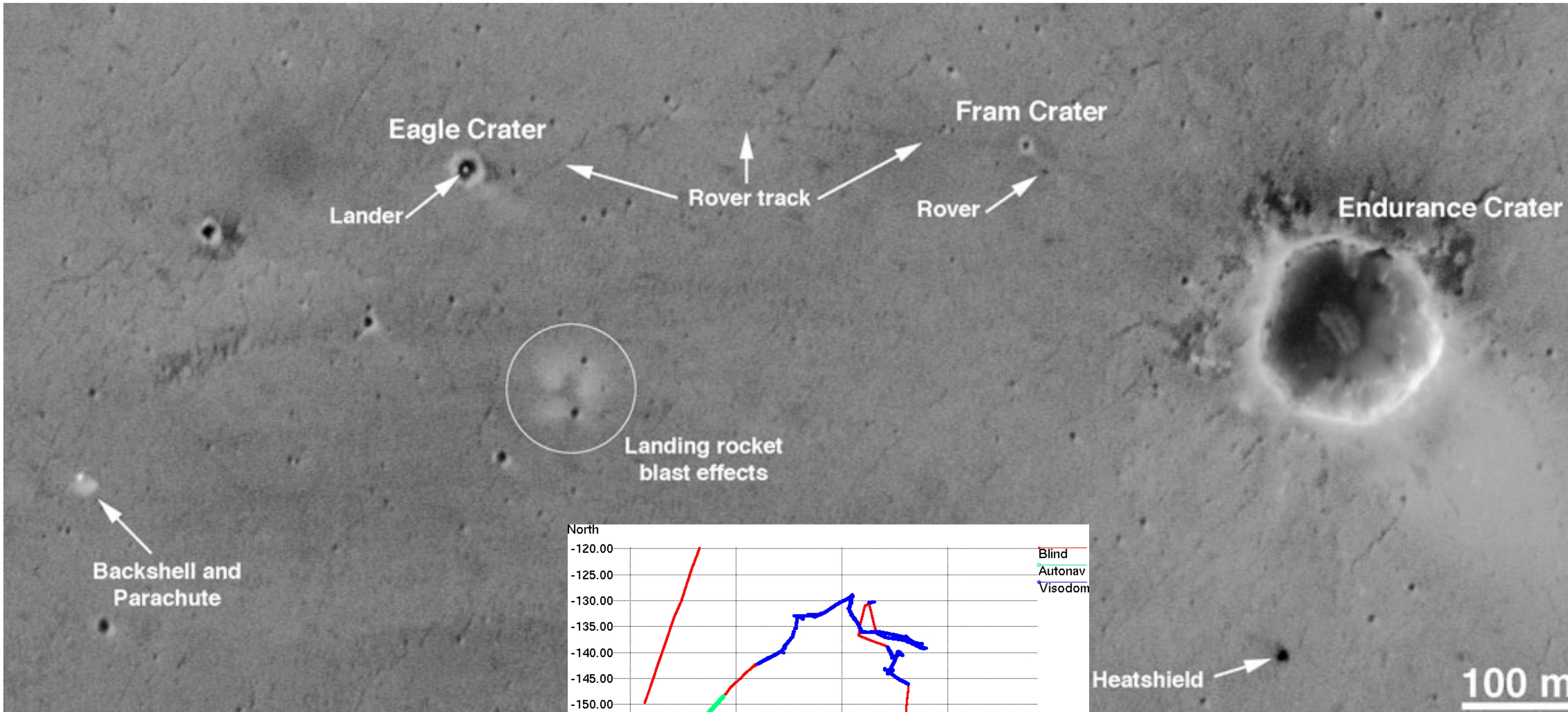
Opportunity Drive through Sol 410



NASA/JPL/MSSS

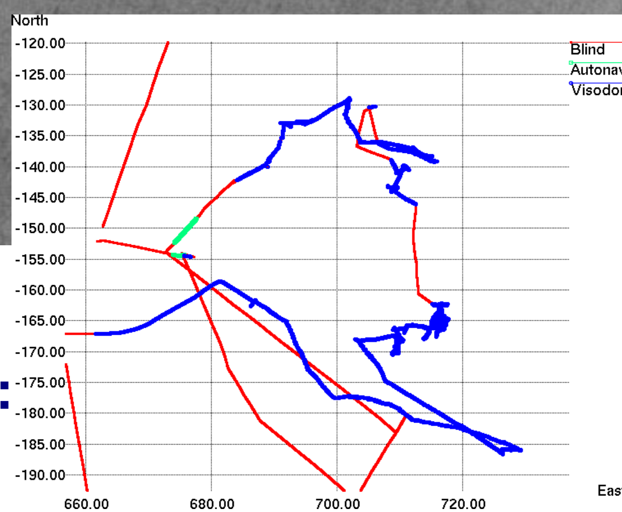
Driving Modes:
Blind
Autonav
Visodom

Opportunity Drive to Endurance Crater

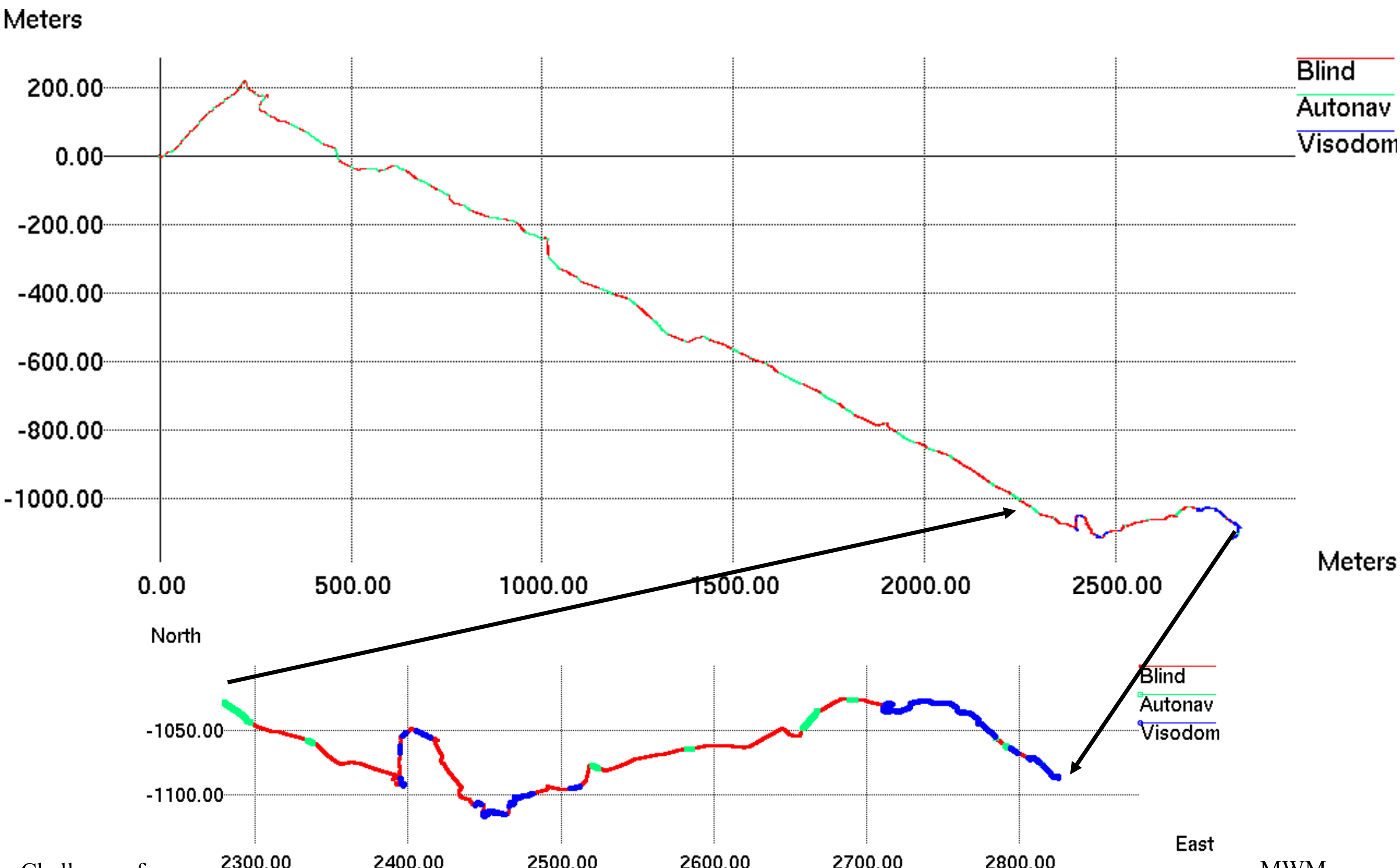


NASA/JPL/MSSS

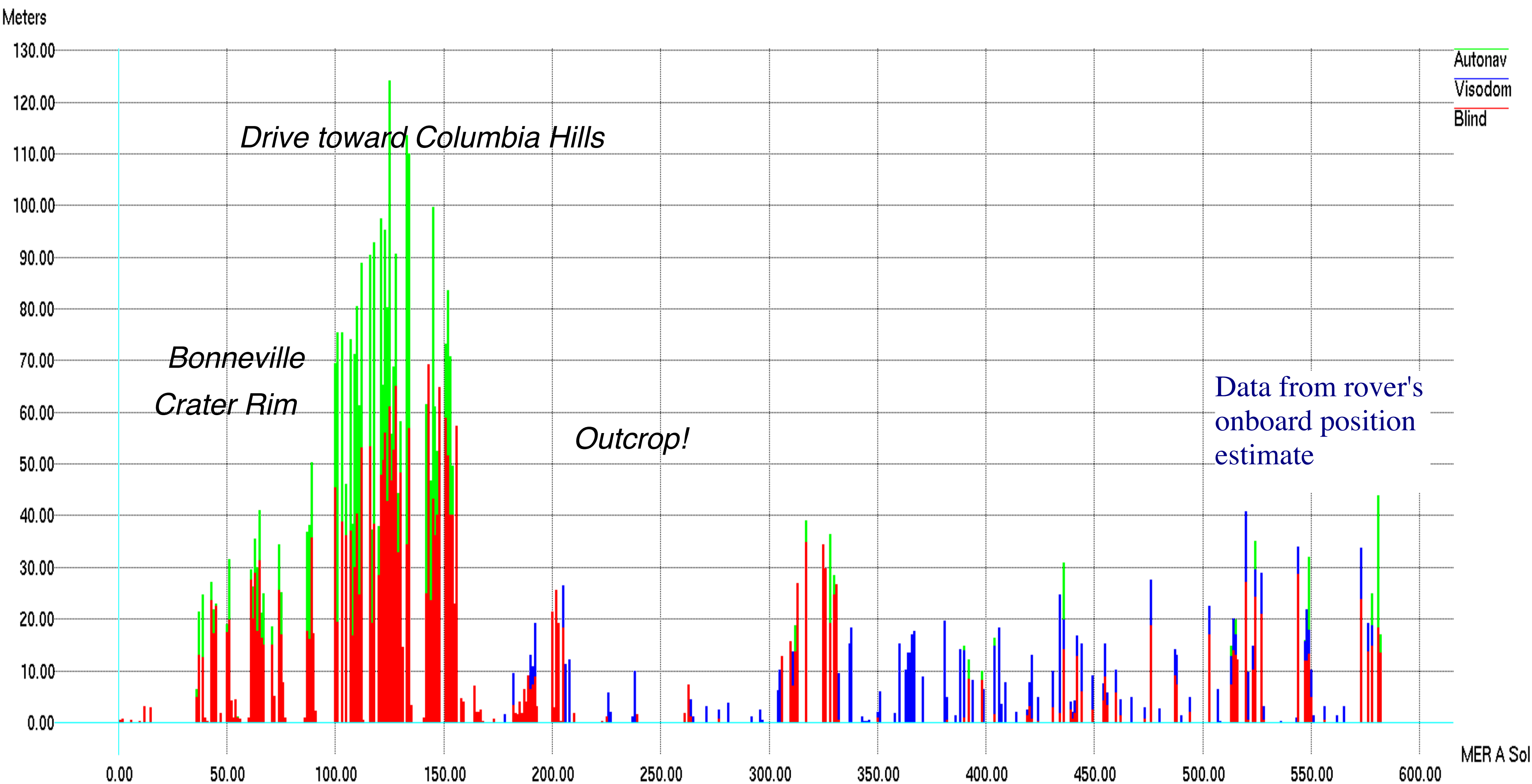
Inside Endurance Crater:



Spirit Drive through Sol 418



Spirit Drive History through Sol 588



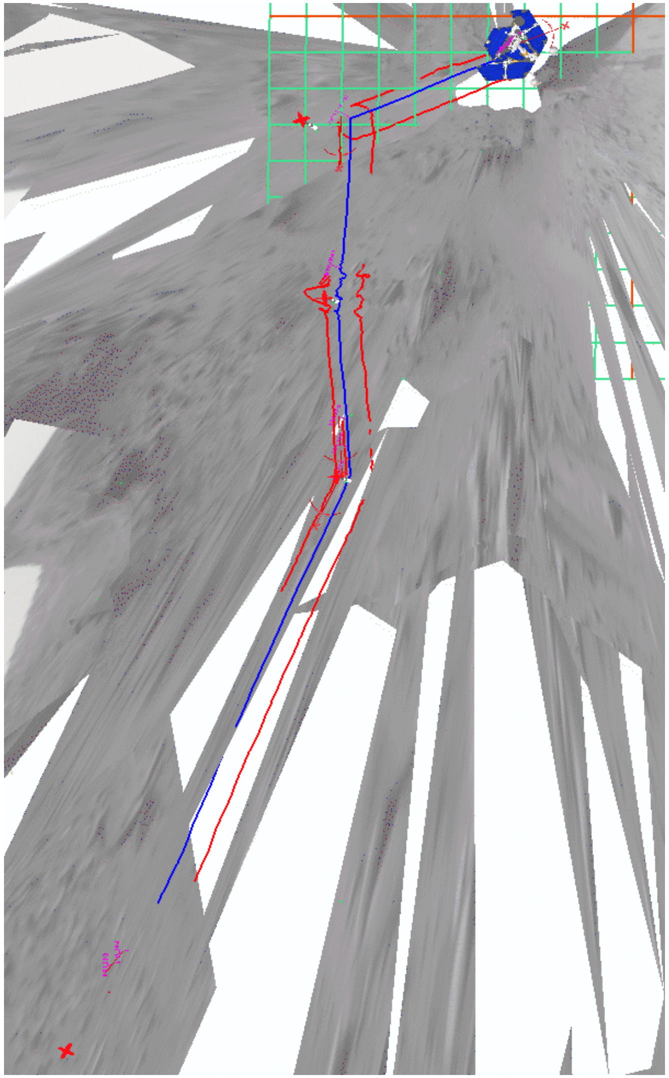
Drive Constraints

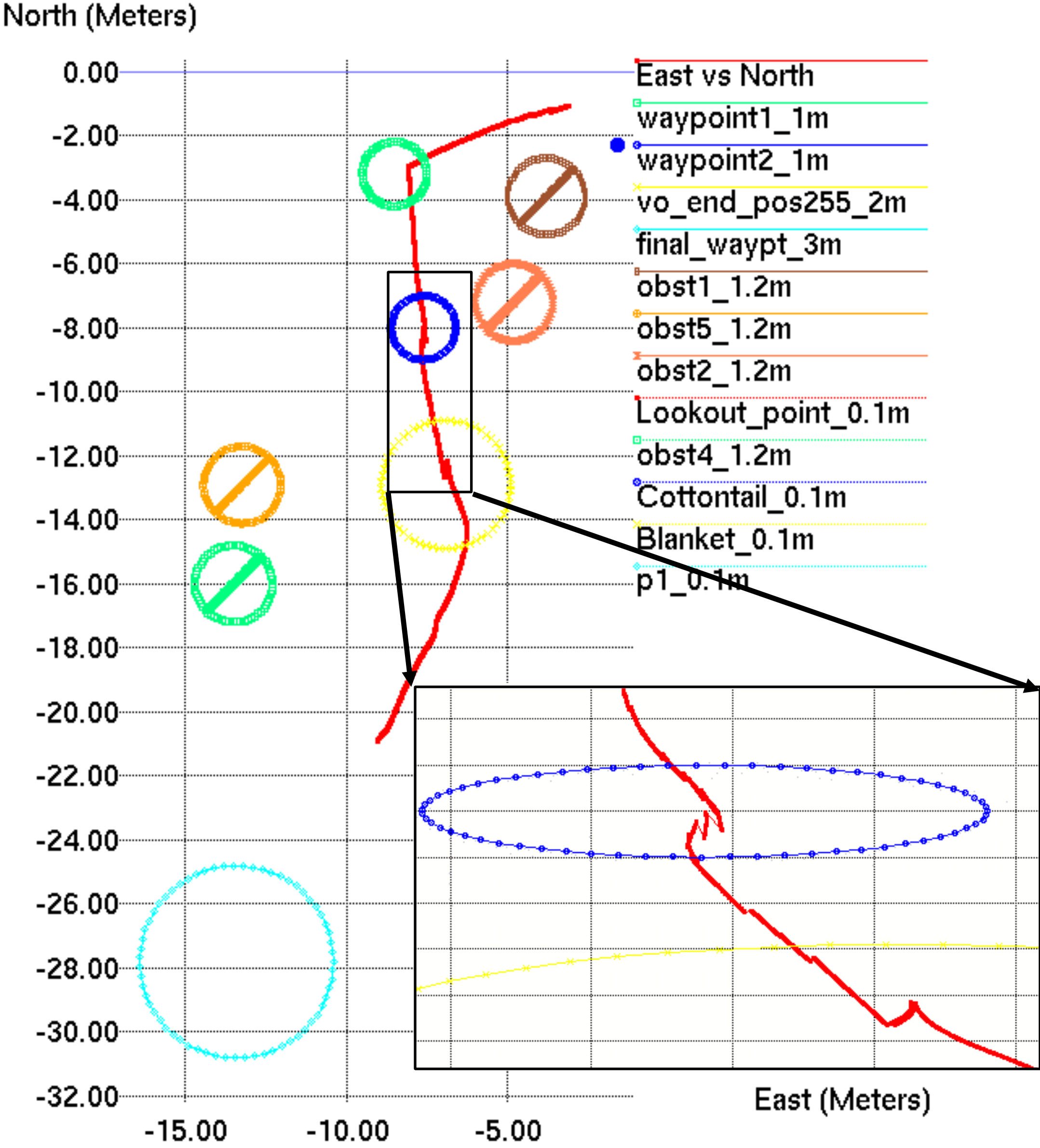
- Typically only enough power to drive 4 hours/day
- Rover generally sleeps from 1700 – 0900; humans plan next day's activities while it sleeps, e.g. human terrain assessment enables a blind drive
- A single VisOdom or AutoNav imaging step takes between 2 and 3 minutes (20MHz CPU, 90+ tasks)
- Onboard terrain analysis only performs geometric assessment; humans must decide when to use VisOdom instead of/in addition to AutoNav
- Placement of Arm requires O(10cm) precision vehicle positioning, often with heading constraint

A-436: Exercising 3 Drive Modes

- Here’s an example of a sol that used 3 drive moves
- The drive plan for Spirit's Sol 436 was:
  - **Back up 5m cross-slope**
  - **Drive upslope with VisOdom using 2 waypoints**
    - **Run Obstacle Check in parallel**
  - **Bear right and run AutoNav (no more VisOdom) to climb a reduced slope in unseen area**
- One last note says:
  - ***This avoids the 25deg slopes along the front ledge on the upslope***

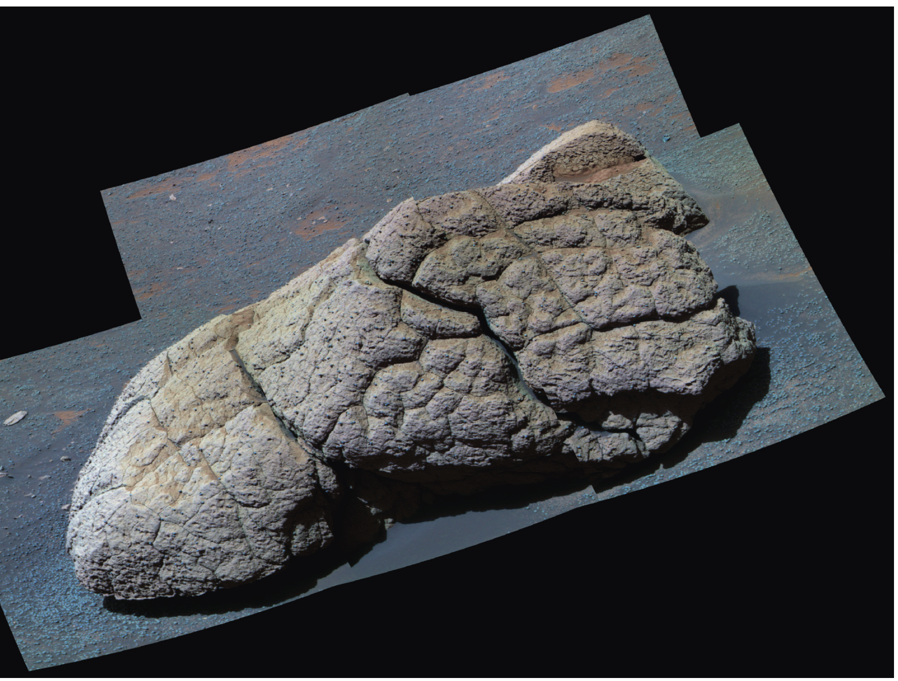
Planned vs. Actual Drive: A-436

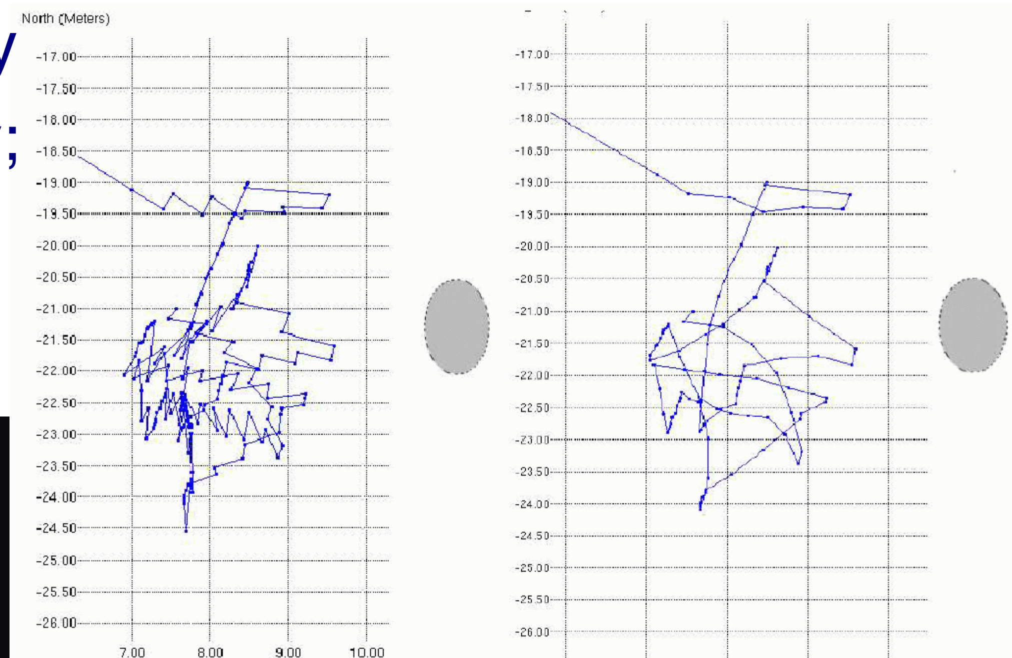




Ensuring Vehicle Safety: Keep-out Zones

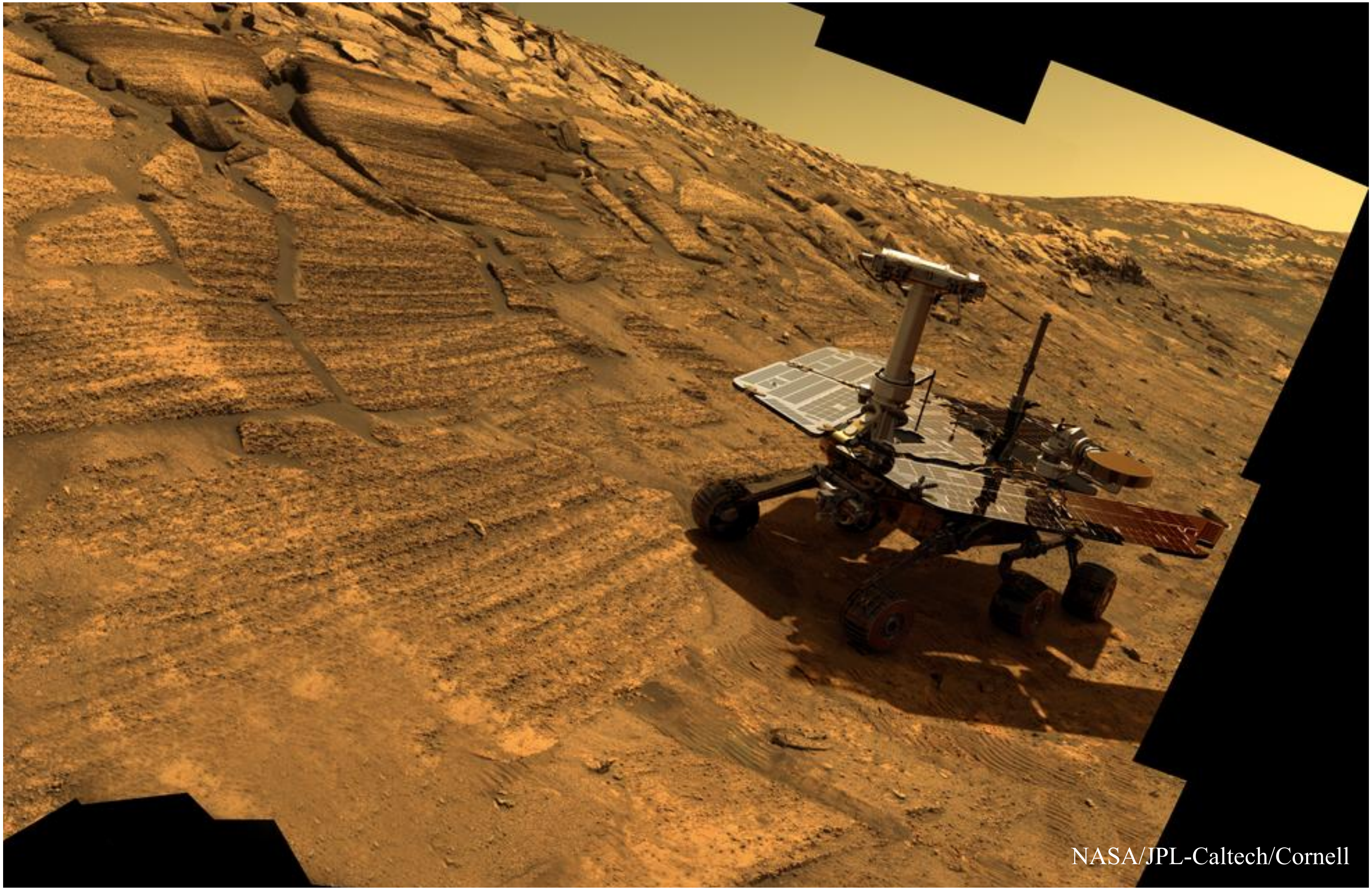
From Sol 249-265, Opportunity kept sliding back into Wopmay; high slip, buried rocks, not enough uphill progress





Each time VisOdom noticed the failure to make progress and prevented driving into it.

Special Effects: Opportunity at Endurance



Summary

- Visual Odometry has proven a highly effective tool for driving in high-slip areas
- Tangible benefits:
  - **Increased Science Return**
    - **Provided robust mid-drive pointing**
    - **Enabled difficult approaches to targets in fewer Sols**
  - **Improved Rover Safety**
    - **Keep-out zones**
    - **Slip checks**

Autonomy Tradeoffs

- Benefits:
  - **Adapts to current vehicle state**
  - **Can drive into unknown areas**
  - **Faster planning time**
- Disadvantages:
  - **Can be order of magnitude slower than Directed**
  - **VisOdom cameras need to be manually pointed**
  - **VisOdom-only mode needs manual Keep-out zones**
  - **Only geometric terrain classification; cannot predict high slip areas**
  - **Unknown use of resources and final state**

Directed Driving Tradeoffs

- Benefits:
  - **Fastest execution time**
  - **More “predictable” final state**
  - **Strategies may be adapted daily**
- Disadvantages:
  - **Can only drive as far as you can see**
  - **Needs much more planning effort**
  - **Limited terrain adaptability; yaw knowledge only**
  - **Cannot plan mid-drive precision imaging with slip**

Future Work

- Speed up onboard processing (e.g., less precise slip check)
- Take advantage of new software:
  - **Global path planner Field D***
  - **IDD Auto-placement (Go and Touch)**
  - **Visual Servoing (Visual Terrain Tracking)**
  - **Autonomous Science (Dust Devil and Cloud Detection)**
- Autonomous Terrain Classification
- Ground-based drive plan assessment allowing for uncertainties (e.g., slip)
- Precision vehicle and instrument placement
- Paradigms for sequence re-use